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Guidelines for the Air-Sea Interaction Special Study: An Element of the NASA Climate Research Program

JPL/SIO Workshop Report

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National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California



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PREFACE

The basic goal of NASA's Climate Research Program is to develop a space capability for global observations of climate parameters which will contribute to our understanding of the processes which influence climate and its predictability. The NASA program is a significant segment of the U.S. National Climate Program which encompasses the broad national effort ranging from paleoclimatology to climate impact assessments.

Four principal areas in which research will be sponsored by NASA are:

- o Data Base Development: To demonstrate and facilitate the use of space-acquired data sets for climate applications and studies;

- o Special Studies: To gain insight and understanding of the physical processes and connections between climate variables, to develop parameterizations for climate models, and to aid in future sensor developments;

- o Climate Modeling and Analysis: To develop climate modeling capabilities to guide the design of the observing system, to optimize the utilization of space-acquired data, to carry out physical processes studies, and to help assess climate predictability; and,

- o Climate Observing System: To develop a climate space-observing-system including operational system improvements, new instruments, and research satellites as needed, as part of an integrated system composed of complementary and mutually supporting elements.

Climate "special studies" involve detailed investigations of atmospheric, hydrospheric and cryospheric structure, composition, and phenomenology of a variety of processes believed to be significant in influencing climate and of studies of instrumental concepts for measuring relevant parameters. The knowledge gained from such studies will aid in the further development of climate models, in better parameterizing the effects of relevant physical processes in large-scale models, in guiding the search for causal mechanisms of potential predictive value, and developing means of measuring significant variables which are not now measurable.

While the possible range of climate special studies covers an exceedingly broad spectrum, NASA has selected the six areas listed below on the basis of their particular relevance to space observations and related climate modeling activities or by virtue of a notable scientific expertise or technological capability existing within the Agency. Even within the problem areas selected, we recognize that significant expertise and interest already exists within other agencies and the academic community. In some cases, as in air-sea interactions, major experimental endeavors are already being planned elsewhere. Accordingly, most of the special studies will be carried out in collaboration with other agencies and university investigators. These collaborative efforts will be influenced by further planning with the National Climate Program Office and appropriate workshops on these and related topics. The six special study areas to be investigated are:

- Aerosol Effects - Theoretical, laboratory and field investigations of the chemistry and radiative properties of natural (volcanic) and man-made aerosol particles and assessment of their impact on regional and global climate. Guidelines for this special study were issued in February 1979.¹
- Radiation Budget and Extended Cloudiness - Remote and in situ observations of cloud properties and radiation balance components and theoretical studies to develop an understanding of the role played by clouds in the radiation balance which exists between the Sun, Earth, and space, and to aid in the parameterization of clouds in climate models.
- Air-Sea Interactions and Related Oceanic Processes - Theoretical and experimental studies of the relationships of ocean physical properties (heat storage and transport) and surface observables (e.g., currents, temperature, waves) to help understand the heat, hydrological and momentum cycles of the climate system, as well as the global balances of such critical gases as CO₂.
- Cryospheric Processes - Remote sensing oriented investigations of sea ice and ice sheet dynamic processes and their relations to climate dynamics through the use of space observables.
- Hydrological Processes Related to Soil Moisture, Evapotranspiration, and Vegetation - Theoretical and experimental studies to assess spaceborne remote sensing methods of observing soil moisture and evapotranspiration parameters for use in climate models.
- Sun/Climate Relationships - Theoretical and experimental investigations of the physical mechanisms by which changes on the Sun affect the Earth's weather and climate.

This report is the product of a Workshop, convened at the request of this Office, to recommend a program for the Agency in the area of Air-Sea Interactions. The attendees recognized at the outset that the problem of air-sea interaction could not be defined in terms of separate atmospheric and oceanic interests. The two media are too closely coupled to be regarded as other than two components of a single climate system. It is a system about which little is known but it may represent one of the more profitable areas of attack on the climate problem in the coming decades. At the present time, however, we cannot be sure what the available measurements mean nor how they may be used to predict climate. We are not, therefore, in a position to make rapid advances with a few well-chosen programs. Instead, the emphasis must lie on extending our knowledge in fruitful directions so that major activities can be planned to start in a few years' time. The report reflects this view in all of its conclusions and recommendations.

The execution of a successful air-sea interaction study program is totally dependent upon the involvement of the highest level of research competence in the atmospheric and oceanographic science communities. There is an extensive record of successful involvement of atmospheric scientists with NASA space missions, but oceanographers have hardly been involved. In general, the field of oceanography is an expanding one, there being more problems than good people to work on them. Consequently, the good people are well supported. Space tools are generally unfamiliar to this community and, while they offer some obvious advantages (e.g., broad spatial coverage for synoptic observations), they are usually less precise in those respects in which ships and other surface platforms perform best. It requires a leap of faith, or at least a clear demonstration of the scientific effectiveness of these remote sensing tools, for oceanographers to transfer their activity to areas with which they are unfamiliar.

NASA recognizes the crucial importance of taking active steps to encourage the confidence and involvement of the best elements of these communities, particularly those outside the Agency. The Space Science program has had a notably successful history in this respect, wherein for many years the science community has been actively involved in all stages of planning and execution in partnership with management, NASA centers and industry. This approach has been adopted in implementing the Space and Terrestrial Applications program. The Workshop convened to initiate the air-sea interaction study is an important step in that direction. The sought-after response of the science community will be through the submission of research proposals and personal involvement in future planning exercises. We anticipate this will, indeed, be the end result of the present planning.

The proposals developed by the Workshop represent the views of the participants, and are subject to review before adoption by NASA. They will, however, be used as a basis for planning, and we anticipate that the Agency will establish a Science Working Group for this study and will be able to implement most--possibly all--of the workshop recommendations.

The workshop was planned and carried out by the Jet Propulsion Laboratory, California Institute of Technology, under the guidance of a steering committee, with Tim Barnett of SIO and Richard Zurek of JPL as executive officers. The meeting was held 6-10 August 1979 at the Scripps Institution of Oceanography, University of California, under the chairmanship of Richard Goody of Harvard University. The names of attendees are given in Appendix C. I am indebted to all of the above for their efforts, to Dr. Nierenberg, SIO Director, for permission to hold the workshop at SIO, and to Ms. Carol Snyder and Ms. Elizabeth Daniels of JPL for their expert logistical assistance.

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SUMMARY OF RECOMMENDATIONS

Not enough is currently known about the physical processes involved in air-sea interaction, nor about the ultimate capabilities of spaceborne instruments, to define a program of investigation in specific terms. However, the directions in which real progress can be made and which can lead us relatively quickly to a state of knowledge in which such a specific program can be defined are reasonably clear. This leads to the following recommendations. (The major details and supporting material for individual items can be found in the section or subsection identified by the bracketed numbers.)

- o A major effort needs to be devoted to the preparation of space-based climatic data sets. In order to ensure that this effort receives proper attention, we propose that data management be regarded as a major element in the NASA air-sea interaction program. Specifically, it is recommended that, in order to accumulate as soon as possible an adequate, comprehensive global climate data base, a third-generation archive be designed and implemented within the next year and that a longer term effort be initiated immediately to develop an experimental fourth-generation archive. [3.6, 4.4]
- o In view of the substantial long-term effort that needs to be devoted to research and development in the production and utilization of space-based data sets for climatic research, NASA should create a group or center for climatic data analysis. This group must have a strong research component. [4.4]
- o Funding for the analyses of existing data sets should be augmented and continued beyond the termination of present programs. Such analyses are essential to determine the future path of air-sea interaction studies, and success in this area will attract the attention and interest of the oceanography and climatology communities. [4.3]
- o A strong theoretical program is essential to the overall program in its present formative stage and the Agency should fund studies in universities, research institutions and government centers. [4.1] This program should include the step-by-step development of an ocean general circulation model which would be available as a facility to the oceanography community. [4.2]
- o Space and surface measurements must be related (1) to understand the physical processes producing remotely sensed signals [3.2, 4.7.2], (2) to provide the instrument verification and calibration needed to maintain the integrity of long-term data sets [3.3, 4.7.1], (3) to provide optimum combined measurement systems for obtaining the basic data [3.4, 4.3], and (4) to increase in general our understanding of important physical processes [4.7.2]. This will require carefully designed field experiments at all stages of our investigation [4.7].

- o The development of new measurement techniques must be grounded in a firm understanding of existing instruments and their major sources of inaccuracy. NASA should continue to support the development of improved rain-rate sensors, of advanced atmospheric sounders which can measure temperature and water vapor as close to the sea surface as possible, and of active systems, such as lidars, for air-sea interaction studies. [4.5]
- o NASA should also consider the development of instruments that include, as an essential part of the system, components deployed on the ocean surface. As part of this work, we recommend that NASA develop a low-cost method for determining the position and identification of buoys at the surface. Closely allied with this effort is the requirement for oceanic calibration stations. [4.5]
- o We recommend that air-sea interaction specialists be closely involved in the planning and implementation of new missions currently under consideration (e.g., ICEX, NOSS) which have relevance to air-sea interaction studies. [4.6]
- o A continuous review of scientific progress and directions in the area of air-sea interaction studies is essential. To provide a forum for such discussion and a focus for the entire program, we recommend the immediate creation of a Science Steering Group (SSG) consisting of actual or potential investigators in the field of air-sea interaction. [5]
- o Finally, we recommend that planning for an air-sea interaction mission be an early task for the Science Steering Group. [4.6, 5]

Richard Goody
Workshop Chairman

1. AREAS OF SCIENTIFIC INTEREST

The purpose of this section is to outline current scientific understanding of the role large-scale air-sea interaction plays in climate variations. The broader context of these climate studies is described in the large collection of national and international reports on which this document builds. Thus, the discussion which follows here is not meant to be all-encompassing, but rather to set the stage for the program objectives and elements which follow.

1.1 Weather and Climate

The atmosphere and ocean communicate by means of heat and momentum fluxes through the sea surface. These fluxes are determined by the joint state of the atmosphere-ocean system, and in turn, their effects modify the atmosphere-ocean system on time scales ranging from minutes to millennia.

The dominant effect of the ocean on the long-term climate is through poleward heat transports. A recent budget study by Oort and Vonder Haar using satellite radiation data, atmospheric radiosonde data, and direct upper ocean measurements has indicated (with much uncertainty) that about half of the net annually averaged poleward heat transport in tropical latitudes is carried by the ocean.¹⁻¹ The implication of this study is that the Earth's long-term climatic state cannot be understood without understanding ocean heat transports. Since all the heat the ocean acquires in low latitudes and releases in high latitudes passes through the sea surface, the study of air-sea interaction becomes a major requirement in the understanding of the Earth's climate.

On shorter time scales, weeks to years, correlation studies involving oceanic and atmospheric data, and simulation studies using large general circulation models of the atmosphere, have indicated that variations in oceanic sea surface temperature (SST) can, through air-sea interaction, have a decided influence on regional weather over populated land areas. It has been suggested, for instance, that Pacific Ocean anomalies can produce large annual variations of winter severity over the continental United States and that Arabian Sea anomalies can affect the intensity of the monsoon rainfalls over the Indian subcontinent.

Neither the causes of sea surface temperature anomalies nor the mechanisms by which they alter the state of the atmosphere are yet fully understood. Remote sensing of the ocean surface over vast expanses of the world's oceans may be the only way to understand, and ultimately to monitor, the effect of the global ocean on the atmosphere at the shorter climatic time scales.

1.2 The Atmosphere

The sensitivity of atmospheric weather and climate to processes involving the underlying ocean is probably greatest in the tropics where the rms temperature variabilities of the troposphere and upper ocean are

comparable and where air-sea correlations are large, both locally and over large distances. In mid-latitudes local correlations are weaker and distant ones even more so. Air-sea fluxes are large at these latitudes, particularly in the western parts of oceans, but the atmospheric components in the bulk flux formulae are much more variable than the oceanic ones. Both numerical and statistical model studies indicate that the atmosphere responds in mid-latitudes to changes in oceanic surface conditions in the tropics. This result may reflect the strong interactions between the tropical and higher latitudes caused by transport of heat and momentum from the tropics poleward to sustain mid-latitude circulation systems.

The results of general circulation simulations indicate that in tropical latitudes, the time-averaged atmospheric circulation is determined, to a large extent, by the distribution of temperature on the underlying surface. There is a strong tendency for rising motion to develop over regions of high surface temperatures and sinking over regions of low surface temperatures. This is true even in model simulations which do not incorporate a hydrologic cycle, although the resulting motions are considerably weaker.

The question of how strongly the pattern of tropical precipitation is tied to the underlying distribution of SST in the tropics is of great importance in verifying the modeling simulations and, ultimately, for an understanding of the global climate system. Of particular interest is the relation between seasonal anomalies in SST and precipitation. During the interannual El Niño phenomena in the equatorial Pacific, for instance, warmer water directly off of Peru is highly correlated with anomalous torrential rainfall in the Peruvian desert plains. Furthermore, anomalously warm water across the entire equatorial Pacific correlates strongly with increased rainfall over much of this region.

1.3 The Air-Sea Interface

The fluxes at the air-sea interface are of primary significance to any understanding of climatic variation. Their immediate effect is felt in the atmospheric boundary layer and the oceanic mixed layer. Both the interior atmospheric and oceanic layers are affected through communication with their respective boundary layers. Thus, understanding the physical processes which define these boundary layers is essential to understanding climatic variability. An adequate description of boundary layer dynamics is also crucial to realizing the potential of remote sensing capabilities by relating the physical quantities that can be measured to those that are needed.

1.3.1 Adjacent Boundary Layers

The atmospheric boundary layer interacts with the rest of the atmosphere through entrainment at the boundary layer top, through deep convection in disturbed areas, and through systematic uplifting in frontal zones. The quantities required for description of these energetic

interactions include the height of the boundary layer, large-scale divergence or convergence, latent heat content (water vapor), sensible heat content, and net radiation.

Although the interaction between the mixed layer and the deeper ocean is not fully understood, entrainment and deep convection are again important. Indeed, just as the atmospheric boundary layer can extend to the tropopause in the Inter-Tropical Convergence Zone, the oceanic mixed layer can extend to the sea bottom in areas of deep convection. This deep convection occurs intermittently in very limited areas (Gulf of Lyons, Norwegian Sea, Weddell Sea, etc.), but has extremely important consequences for the general circulation and stratification of the ocean. The discovery of some surface signature of the deep convection and its monitoring from space would be of great value.

Many problems of mixed layer dynamics remain outstanding. Only recently have the dynamics and role of diurnal variations of the mixed layer begun to be addressed. The nature and role of dissipation, and, for instance, the problem of heat transport through the bottom of the mixed layer require clarification and quantification. Finally, the climatological effects of storms on both the atmospheric and oceanic boundary layers and of the air-sea interface on the air and cloud masses above it need to be better observed and understood.

1.3.2 Sea Ice

The presence of sea ice has a profound effect on the interchange at high latitudes of heat and momentum between atmosphere and ocean, and through the latent heat of fusion, on their local heat budgets. Future studies using atmospheric circulation models need to quantify the effects of heat flux changes due to varying sea ice cover on the wind and temperature fields both locally and in lower latitudes. Feedback from atmospheric winds and near-surface oceanic circulation on the extent and packing of sea ice is an important but ill-understood process. Statistically significant relationships have been established between sea-ice limits and large-scale atmospheric circulation features such as temperature and pressure. There is little information, however, on the specific physical mechanisms underlying these relationships or their pertinent time and space scales.

The sea-ice-air interface will be studied as part of a NASA cryospheric exchange processes program, but the importance of air-sea interactions involving sea ice to the polar climate and to the possible influence on global climate requires that at least these aspects of the air-ice-sea interactions be addressed in this study. The two programs can be coordinated once their various elements are defined. Hopefully, this approach will ensure that the regional and global effects of this very important component of air-sea interaction will not be overlooked.

1.4 The Ocean

1.4.1 The Heat Budget of the Upper Ocean

The upper ocean (i.e., above the main thermocline) is the locus of all relatively short-term (annual and interannual) heat storage changes. Its ability to store heat in summer and to give it up in winter has a crucial effect upon the climate of the temperate latitudes. The important components of the oceanic heat budget vary with the geographical location, depth and frequency range of interest. The budgets of the mixed layer are often different from those of the upper few hundred meters; those of the near-surface, mid-latitude, mid-ocean regions are different in summer and winter, etc. Understanding the global ocean heat budget thus requires the ability to measure all the significant components of the budget, though not necessarily in all locations at all times. Most of the heat that enters or leaves the ocean does so through the sea's surface -- via radiation, latent and sensible heat fluxes. A given volume of ocean is affected by lateral and vertical advection of heat as well as surface fluxes.

A wide variety of ocean responses to different processes appears to exist. Surface cooling can produce shallow or deep convection (depending on the magnitude of the cooling and underlying density structure). Wind stresses drive Ekman and other currents that provide significant advectons, as well as the energy used to mix and entrain within the mixed layer. Heat advection also results from both steady currents and strongly time-dependent motions on various spatial scales. In the long-time average, the latter motions produce an "eddy heat flux." Each of these processes is probably important somewhere in the ocean.

The study of the heat budget of the upper layers of the ocean is the principal objective of a number of current oceanographic experiments (NORPAX, MILE, JASIN, etc). The most recent analysis of upper ocean thermal data and surface heat fluxes indicates that in the central and northern Pacific the rate of heat storage in the mixed layer and the computed fluxes balance on the seasonal time scale. On the other time scales in this region, advection can also be important. South of 20° N latitude, vertical motions of the main thermocline are important for the upper ocean budget. Within 10° of the equator and in the western boundary areas, lateral advection of heat can be significant on all time scales, but quantitative estimates are difficult because of the paucity of ocean current data.

Outside the regions of strong currents, the seasonal oceanic heat storage should be dominated by the local heat fluxes into the ocean, perhaps supplemented by local entrainment from below. However, it is precisely in the dynamically controlled western boundary and equatorial regions that most of the heat exchange across the sea surface takes place. Air-sea interactions are also particularly intense during strong individual storms, and these special periods may account for much of the exchange that causes sea surface temperature anomalies and water mass formation events. Because of the temporal intermittence of these processes, the ability to observe frequently and with broad geographical coverage is essential.

Determination of the air-sea fluxes, heat storage, and heat advection contributions needed to understand the heat budget of the ocean in the different regions of the world is beyond the capability of present oceanographic research tools. Extended geographical coverage, particularly in the Southern Hemisphere, as well as more data on fluxes and currents are needed. New ways of obtaining these data from remote sensors are urgently required.

1.4.2 General Circulation of the Upper Ocean

Scale analysis as well as simulation experiments with oceanic general circulation models suggest that meridional overturning is a major poleward heat transport mechanism. The mid-ocean near-surface currents are probably geostrophic and/or directly wind forced (Ekman currents), so that observations of wind stress, vertical density field and sea surface height (or currents at some depth) are all needed to infer them. The low-frequency deep currents are generally assumed to be geostrophic and so estimates require good density field information and currents at a reference level; these data are generally unavailable. Strong current systems such as the Gulf Stream, Kuroshio, Somali Current or Equatorial Undercurrent, which may be major transporters of heat, are more complex and their structures are correspondingly more difficult to infer. Our knowledge of sub-surface currents in the ocean is rudimentary at best and largely negligible over much of the Southern Hemisphere.

Much of the near-surface flow is forced either directly or indirectly (by inducing pressure gradients) by the wind stress field. In many regions the wind field is strongly variable in space and time, and is only sporadically sampled over the ocean, particularly in the Southern Hemisphere. Given the presently available wind stress information, many fundamental ocean and climate process modeling questions cannot be investigated realistically.

Satellite microwave instruments may provide the first good global surface stress fields. Considerable work with surface-based measurements (i.e., surface truth) remains to be done to determine the accuracy of the inversion algorithms under the full range of ocean surface conditions. Once their utility is established, these techniques will provide uniquely useful data for ocean and climate modeling.

Observations of sea level from islands in the tropical Pacific have been shown to be correlated with thermocline motions and with baroclinic currents. If sea surface topography can be adjusted to give the surface dynamic topography, then surface geostrophic currents can be evaluated. Time rate of change of sea surface height, properly corrected for tides, surface pressure, etc., can provide surface geostrophic current changes even if the geoid is not known. Height information on a global scale would be very valuable.

1.4.3 Synoptic and Evolutionary Studies of Ocean Surface Phenomena

Synoptic studies have proceeded slowly in part because of the great difficulty of assembling surface-based data. It has been repeatedly demonstrated in meteorological studies, however, that until full four-dimensional representations become available, identifying and understanding the underlying physical processes associated with the above studies is a matter of guesswork. The availability of such data will have a revolutionary influence on ocean surface layer studies, but will require measurement programs that use both direct measurements of the oceanic/atmospheric boundary layers and remotely sensed near-surface information.

2. SCIENTIFIC OBJECTIVES

Climatic effects of air-sea interaction cannot be adequately understood without considering the full range of spatial and temporal scales covering the physical processes which produce interactions at the air-sea interface. These processes are best studied in the context of the coupled two-fluid system, and both the atmospheric and oceanic parts of the system need to be fully understood. Each of the following subsections addresses a major facet of this coupled system by presenting a general scientific goal followed by a short list of more specific items requiring better understanding. The lists are derived from the material presented in the previous sections, and supporting material is cross-referenced by indicating the number [in brackets] of the appropriate section or subsection. The lists are not all-inclusive, and the state of our present knowledge is such that they will undoubtedly change as more information and theoretical insights become available.

2.1 The Atmosphere

The overall goal in this area is to understand the influence of the ocean on the atmospheric general circulation. This will require studies of the following:

- a) The sensitivity of climate to anomalies in different oceanic regions. [1.1, 1.2]
- b) Teleconnections (i.e., observed patterns of correlated climatic variations) and their underlying physical processes. [1.1, 1.2]
- c) Storm and air mass modification, particularly over western boundary currents, over strong sea surface temperature (SST) anomalies, and over sea ice. [1.2, 1.3]

2.2 The Air-Sea Interface

The primary scientific objective of any air-sea interaction program must be an adequate description and better understanding of the fluxes of heat, momentum, and mass (evaporation, rainfall) across the air-sea interface. In support of this objective, the following items need to be studied:

- a) Turbulent and mean structure of the layers immediately adjacent to both sides of the air-sea interface. [1.3]
- b) Entrainment, mixing and dissipation in both turbulent boundary layers. [1.3.1]
- c) The effect of the passage of fronts (in the ocean as well as the atmosphere) and of big storms. [1.3]
- d) Mechanisms controlling and affected by sea ice. [1.3.2]

2.3 The Ocean

A major goal of climate studies is to determine the amount of heat transported poleward by the ocean and to understand how this transport is accomplished. The attainment of this goal will require studies of the following:

- a) Relative sizes of the various components of the oceanic heat budget (including mixed layer storage, transport and exchange) in different regions of the world ocean and on various time scales. [1.1, 1.4.1]
- b) Generation of sea surface temperature anomalies. [1.1, 1.4.1]
- c) Steady and time-dependent oceanic response to surface wind stress. [1.4.2]
- d) Ocean currents and their dynamics. [1.4.2]

3. RESEARCH STRATEGIES

3.1 Introduction

The climatic studies needed to attain the goals outlined in Section 2 will require planetary-scale, long-term data sets. Remote sensing from satellites offers unique capabilities for providing such data. The satellite data are global, they are synoptic, and the data can be long term. They are not, however, simply a reproduction of the sea surface variables which oceanographers have conventionally measured (from ships, buoys, etc.). Table I outlines current remote sensing capabilities for measuring quantities relevant to air-sea interaction studies; a more comprehensive discussion of these capabilities is given in Appendix A. As the discussion in Appendix A reveals, remote sensors on satellites cannot by themselves provide all the measurements needed to understand air-sea interactions. However, only satellite platforms can provide the general coverage required for a climate data base.

TABLE I

SUMMARY ASSESSMENT OF PRESENT REMOTE SENSING
CAPABILITIES FOR AIR-SEA INTERACTION STUDIES

Parameter	Data	Accuracy	Spatial Resolution
1. Sea Surface Temperature	Available	2 K (absolute)	Adequate
2. Air-Sea Temperature Difference	Inadequate	TBD (± 1 K)	TBD ^a
3. Atmospheric Temperature Profiles	Available	2 K	Adequate
4. Humidity Profiles	"	Factor of 2	TBD
5. Precipitable Water	"	10-50%	TBD
6. Rainfall	"	50%	TBD
7. Cloud Amount	"	5-50%	Adequate
8. Cloud Top Height	"	0.5 - 1 km	Adequate
9. Surface Salinity	Inadequate	0.5 ppt	TBD
10. Wind Speed	Available	1 - 3 m/s	TBD
11. Wind Vector	"	0 - 15 deg	TBD
12. Surface Ocean Currents and Drifts	"	1 m/s	TBD
13. Sea Level Height	"	20 - 50 cm	TBD
14. Thermocline Depth	Not Available	TBD	TBD
15. Sea-Level Pressure	Not Available	TBD (2 - 3 mb)	200 km

^aTo Be Determined

This section presents various research strategies designed to enhance the utility of remotely sensed data, so that the data needed to conduct the studies outlined in Section 2 can be obtained. These strategies underlie many of the program elements which follow in Section 4 and are built around the following conceptual elements: (1) understanding the physical processes which produce and modulate the remotely sensed signal; (2) instrument verification; (3) combining the capabilities of several different remote sensors or of remote and in situ capabilities to measure a given variable; (4) utilizing the directly sensed remote measurements; and, (5) comprehensive data management. The successful implementation of these concepts depends to a very large extent on the direct involvement of those oceanographers and meteorologists who are knowledgeable and actively working in this field. This involvement is needed at all stages of the program and includes selection of measurement objectives and criteria, the design of needed instruments, as well as involvement in the observational and data analysis stages.

3.2 Understanding Satellite Signals

In many cases the satellite returns information that we do not fully understand how to interpret. Often this can be directly linked to our lack of understanding regarding the processes which give rise to that signal. In other cases it may be that we have not yet learned how to best use the signal to understand a geophysical problem.

For instance, much of our current understanding of ocean/atmosphere interactions are based on parameterizations of air-sea heat exchange, momentum exchange, etc. Many of these parameterizations are based on surface data and numerical schemes developed over a half century ago by scientists such as Brunt and Angstrom.^{3-1, 3-2} Radiation parameterizations, for example, are based on meager data from perhaps a few continental stations. The satellite, however, measures radiation over the whole globe. A few well designed field experiments in different types of environments could relate the satellite estimates of radiation to the more conventional ones now used to study climatic change. In the long run new parameterizations based upon satellite data may be derived that would be more fundamental and useful for studying the Earth's radiation budget than those currently in vogue.

Many of the satellite signals are strongly influenced by conditions at or very close to the air-sea interface. Yet we know very little about the mechanical processes, indeed even the mean distribution of variables such as velocity, in the layers within a few meters of the ocean/atmosphere interface. Even concepts such as surface velocity or surface roughness are controversial. Thus, to understand the meaning of the satellite signals, we have to understand the physics of this ocean/atmosphere interface more completely. For instance, the scatterometer appears to be a most promising device for the measurement of "surface wind." The scatterometer return is affected primarily by the small-scale capillary wave field. These tiny waves are affected by wave conditions, currents, atmospheric stability, the presence of surface films, etc., factors which need have no relation to the "local" wind the scatterometer is trying to sense, yet which can all affect the scattering cross section. A well-designed

set of experiments to determine the effects of these natural variables on the scatterometer returns could provide the atmospheric and oceanographic community with a quantitative assessment of the true nature of these "wind" measurements.

3.3 Instrument Verification

In many cases the algorithms used to convert raw satellite information to an observable surface parameter require additional testing, particularly if the algorithm is largely statistical in nature. It is important that every opportunity be taken to carry through such tests.

A good example in this subject area is the recent successful flight of SEASAT. The calibration algorithms were largely developed during the Gulf of Alaska program. While these algorithms will be independently checked on the JASIN data set, the algorithms could be further tested by comparing them with observed winds in the equatorial Pacific Ocean. The observations are not of exceedingly high quality, but they nevertheless exist in an area where the wind speeds are low, humidity is high, and the potential effects of current systems on the ocean scattering properties could be extensive. Similar comparisons could be made in the Southern Hemisphere, again with either ship observations or data from instrumented towers. During the three months of the SEASAT flight there were large storm systems in this part of the world that would afford tests of the calibration at high wind speeds.

SEASAT altimetry data could also be used to compare satellite estimates of the slopes and the time rate of change of sea level with data from a large array of existing measurement stations in such regions as the equatorial Pacific. By looking at the time rate of change one could avoid the geoid uncertainty problem and obtain an idea of the measurement errors associated with orbital uncertainties.

These are but two examples of the kind of additional studies that must be conducted with existing and future data to not only ensure the accuracy of the algorithms used to produce the data, but also to produce potentially interesting scientific results.

3.4 Multi-Sensor Approach

In many cases the potential of satellite data is greatly enhanced when several instruments are used in combination or when remote and in situ measurements are combined. For instance, one of the most discussed and used products from satellite systems are measurements of sea surface temperature (SST). Both of the currently existing satellite techniques for estimating SST have unique problems (Appendix A). Present measurements taken at infrared wavelengths are degraded when there are clouds in the field of view, while the multi-spectral microwave technique (e.g., SMMR) is sensitive to sea surface roughness and other variables which affect the surface emissivity. In the future, the following two concepts could alleviate some of the instrumental difficulties:

I. The advantages of combining the microwave and infrared information for the purposes of measuring SST should be investigated by conducting a properly planned experiment which uses both IR and microwave radiometers. A combined system could result in getting SST measurements over the global oceans on a day-to-day basis with an accuracy that might be substantially better than that provided by either one of the two individual systems. [2.3b]

II. Remotely sensed measurements could be combined with in situ measurements to provide a global picture of the SST field. The in situ measurements could be valuable in two ways: 1) In cases where remote sensing methods are capable of making accurate measurements, in situ measurements will be needed for quality control to ensure that the satellite-based sensors are not degrading with time and to provide a means to recalibrate the sensors. This is crucial in any long-term monitoring program in order to avoid "climatic anomalies" associated with changing sensors and/or calibration algorithms; 2) In cases where neither of the candidate satellite systems can provide the required information, then the in situ estimates of SST can be used to provide the necessary continuity for global mapping. [2.3b]

3.5 Utilization of the Direct Satellite Measurements

The fluxes of heat, momentum, and mass at the air-sea interface are difficult to measure even with ground-based instruments, and the prospects for direct measurements of these quantities from a satellite are not promising in the immediate future (see Appendix A). Nevertheless, satellite data may already provide a clue to these fundamental quantities. For instance, it may be that the radiation measurements already on hand are strongly related to conventional estimates of air-sea heat exchange. Simple regression studies on existing data could examine this possibility. Numerous parameterizations in the heat budget equation are based on old data and could be redone in view of new satellite information. If the reparameterization could be done in terms of variables measured directly from space, satellites could provide proxy measures of the air-sea heat exchanges that are so vital in climate studies.

Satellite measurements could also be utilized to verify numerical simulations of air-sea interaction [2.2] if the models produce the necessary fields. For instance, a boundary layer model that simulates temperature and water vapor in the atmospheric boundary layer and sea surface temperature could produce fields of IR radiance which could be compared with satellite observations. Other potential points of comparison include the height of the boundary layer or the position of fronts.

3.6 Data Management

At present there is an enormous and widening gap between the rapidly growing archive of space-based data becoming available for climatic research and the limited capability of individual scientists for processing, analyzing and interpreting it. In some cases, potentially valuable data sets are not even being archived in digital form because of the inability

of the present data management system to deal with the large volumes of data. At the same time, the rate of progress on certain key scientific problems is being impeded by lack of access to these same data. In order to bridge this gap the essential information needed by individual scientists must be distilled from the vast array of raw satellite data in the form of a hierarchy of compressed or summarized data sets. High-resolution satellite imagery presents a particularly difficult problem from a data management point of view because of the extremely large data volume involved, but even here it is possible to outline a hierarchy of summarized data relevant to climate research:

A first-generation archive would consist of photographic images or of subjectively analyzed summaries of the images. Much of the existing satellite imagery exists only in this form. These data are of limited use for quantitative purposes.

A second-generation archive would consist of variables of scientific importance, such as spectral radiances, averaged over specified areas, probably on a standardized grid.

A third-generation archive would consist of the above data, plus histograms constructed from the mesoscale image elements within the averaging area to provide a statistical summary of the higher resolution elements of the field. Such histograms could represent, for example, the fractional areas within a given grid square covered by clear sky, deep convective clouds, and cloud decks in various height ranges.

A fourth-generation archive would consist of the variables described above plus information on scientifically important variables derived by combining data from two or more separate sensors. For example, data from the visible or window IR channel would identify the cloud-free areas within a given grid square so that these areas could be sampled by other sensors to determine sea surface temperature, salinity, wind stress or atmospheric precipitable water. Such conditional sampling techniques could extract a considerable amount of additional information from satellite imagery and improve the signal-to-noise ratio in observations of the sea surface.

4. PROGRAM ELEMENTS

This section will describe an exploratory program whose elements (e.g., theory, instrument development, new missions, and data management) will put NASA into a strong position to define a very specific air-sea interaction climate program within the next few years. Such a specific program cannot be defined now because not enough is currently known about the physical processes involved in air-sea interaction or about the ultimate capabilities of space instrumentation. The program elements listed below are intended to advance the present state of knowledge to the point where that program can be defined.

4.1 Theoretical Studies

Modeling and diagnostic studies are needed to design measurement systems and to interpret the resulting data. Although the list should not be regarded as exclusive, the following studies are needed:

- Model process and/or regional phenomena to understand important physical mechanisms (e.g., how is the main thermocline maintained?) and to interpret more complex numerical simulations of ocean processes.
- Model microphysical processes at the air-sea interface which give rise to remotely sensed signals. How are the signals (e.g., SAR, SASS, SMMR--see Appendix B) related to quantities of interest? [3.2]
- Study boundary layer formation: (i) What is the velocity structure in the uppermost oceanic layers? [2.2a,b; 2.3c,d] (ii) Is there an observable signature of deep oceanic formation? [2.3b] (iii) What are the effects of advection on mixed layer processes? [2.3a]
- Understand how the boundary layers are modified by fronts and storms. [2.2c] Existing data (e.g., GATE) can guide modeling efforts in this area.
- Develop atmospheric boundary layer models which relate observable features (such as cloud type, morphology or extent) to surface heat fluxes. [2.2] Such relationships could be inverted to yield surface fluxes in terms of the direct satellite observations.
- Parameterize solar and thermal radiation at the ocean surface in terms of appropriate satellite observables. Both regression analyses and theoretical insights are needed to determine the most useful parameters. [2.2, 3.5]
- Determine the dominant mechanisms controlling the position of the ice edge (wind stress, water stress, surface heat balance?). An interactive model of the wind-driven oceanic circulation in the vicinity of the ice edge is needed. The time-dependent model would include a stratified ocean and a moveable ice edge. Fully coupled air-sea-ice models are not feasible at this time due to the fact that the oceanic part is not well enough known.

- ° Model the sensitivity of the atmospheric circulation to changes in the sea ice and surface fluxes in general. [2.1] Models need greater resolution in space and time than in the past.
- ° Investigate the physical basis of observed climatic fluctuations of the atmospheric circulation. [2.1b] The southern oscillation and the teleconnections between the tropics and mid-latitudes are two prominent examples of phenomena which need to be understood.

4.2 Ocean General Circulation Modeling

The step-by-step development of an ocean general circulation model would provide a valuable complement to the theoretical studies outlined above. NASA should fund the development of such a model as a facility which would be readily available to the oceanographic community. Typically, this will mean that the investigator who wishes to use the model will come to the facility and use the host computer. NASA should supply personnel to maintain the model code and the associated data sets. The model should be designed in a modular fashion so that its physical parameterizations may be readily altered.

Because of our present lack of understanding and of comprehensive observations of many important physical processes, a step-by-step development of the general circulation model is essential. Such an approach would include:

- ° Physical process studies. Studies of mixing and entrainment in the surface layers, of deep convection, of sea ice formation, of upwelling, of boundary currents, and of mesoscale eddies are all examples of the studies needed to parameterize local, small-scale processes for modeling of the larger-scale circulation. Such studies also directly address the scientific objectives outlined in Section 2.
- ° Regional studies. Initially, the large-scale numerical simulations will be regional in scope as the appropriate parameterizations and adequate data for prescribing forcing functions and for model verification become available.
- ° Global studies. Satellite sea level data will provide the first large-scale, near-synoptic data set for verification of ocean models. While such a data set is far from a complete description of the state of the ocean, it will provide more information to verify against than there are tunable parameters in the models.
- ° Sensor simulation studies. Atmospheric GCMs have proven valuable in assessing the potential value of remote sensing data and in developing algorithms for deriving geophysical parameters from the directly measured quantities. Similar uses are envisioned for an ocean model.

4.3 New Analyses of Existing Data Sets

Existing satellite and surface data can be used to answer immediately a number of important scientific and instrumental questions. Before outlining some of these analyses, we first note some potential difficulties that the user will encounter in trying to carry out such studies.

- ° It is often difficult to learn what satellite data are available. Widespread distribution of a guide such as the Satellite Data Users Bulletin is needed.⁴⁻¹
- ° Much of the information needed by the user on the data and instrument quality will have to come from several agencies, e.g., NASA and NOAA. Steps should be taken to ensure that there is interagency cooperation in providing the required information.

Analyses of existing satellite data can be broken down into three general categories:

- ° SEASAT data. The SEASAT data set offers unique measurements which must be completely explored. The present analysis plans are good but the possibility exists for even more extensive investigation of the data. While the comparison with the JASIN experiment is very valuable, many other such comparisons are possible even though the quality of the ground truth may not be as good as in JASIN. [3.3]
- ° Analyses associated with the heat budget. Despite the difficulty of estimating heat fluxes directly from satellite data, every effort should be made to obtain the various components of the heat budget wherever possible. [2.2a] The classic calculations of Oort and Vonder Haar regarding the meridional flux of heat in the atmosphere and oceans should be redone to take advantage of the longer term and simultaneous data sets which already exist for ocean, atmosphere and radiation parameters.¹⁻¹ It may also be possible to reformulate using existing data (e.g., GATE, JASIN) the bulk radiation parameterizations developed originally by Budyko and Jacobs.^{4-2, 4-3} Even if not immediately successful, such a study would suggest the additional measurements needed to solve the radiation parameterization problem. Whatever the results, the possibility of updating and extending the charts of Budyko clearly exists and the task should be undertaken soon. [3.2, 3.5]
- ° Proxy measurements. A regression study might show whether satellite measurements (e.g., brightness temperatures) are strongly related to more conventional estimates of air-sea heat exchange. Another possibility would be to relate, simultaneously, cloud morphology to the large-scale air-sea heat exchange fields that have recently been developed by Bunker⁴⁻⁴ and Clark⁴⁻⁵ for the Northern Hemisphere oceans. [3.5]

New and different approaches to the analysis of existing data must be pursued. Several possibilities were illustrated in Section 3. The methods and techniques of carrying through these approaches should be supervised by a unified science management group to ensure that the latest analysis techniques and user requirements are considered.

In summary, existing satellite data combined with existing surface information can be mined to yield new perspectives on satellite systems in monitoring and investigating large-scale air-sea interactions. The potential for considerable scientific progress is certainly there, as well as much of the information needed to design joint ground-satellite systems and optimal combinations of satellite sensors.

4.4 Data Management

Implicit in the above suggestions is the existence of a well organized, easily useable data base of satellite observations. The contents of such a base must be readily available to the average scientific user who will be interested not only in type and distribution of data but also details associated with its derivation from calibration algorithms, characteristics of the instruments that acquired the data, orbital information, etc. Despite the difficulties of such data management, a beginning on problems like these has been made during the Global Weather Experiment, and so some guidance is available. Clearly, the data base matter will have to be addressed before any large-scale usage of existing satellite data becomes a reality.

In order to prevent the further loss of space-based climatic data due to inadequate archiving and to initiate, as soon as possible, the accumulation of a global data base adequate to support a wide range of climatic research, the following recommendations are made:

- ° Procedures for developing the third generation (see Section 3.6) archive should be designed and implemented within the next year. It is essential that imagery data from the geostationary satellites be included within this archive, since only these can provide adequate sampling of the diurnal cycle. The design of this archive should involve the participation of the research community through the use of consultants, workshops, or advisory committees.
- ° A longer term effort should be initiated immediately to develop an experimental fourth generation archive. [3.6] This will be a more difficult task than for the third generation archive, because it involves data from different sensors. Some experimentation will be required in order to develop appropriate criteria for conditional sampling. Hence, the design of a fourth generation archive will require a substantial research component.
- ° Include both surface and satellite-based data in the third and fourth generation archives in order to preserve essential information about all spatial and temporal scales inherent in the data.

In view of the substantial long-term effort that needs to be devoted to research and development in the production of space-based data sets for climatic research, NASA should create a group or center for climatic data analysis. This group must have a strong research component with responsibility for quality control of the archive. We make no recommendation as to whether the group should be inside or outside the federal government, but both possibilities should be explored. Such a group or center should not duplicate existing facilities. Rather, its possible activities would include:

- ° Develop new techniques for the collection, analysis, archiving, display and distribution of the vast amounts of data that satellites would retrieve.
- ° Reanalyze and archive conventional data in forms suitable for comparison with satellite data.
- ° Analyze and archive satellite data for use within NASA and for distribution to the outside community.
- ° Construct, run and analyze coupled air-sea interaction models. These models would be used for the analysis of raw data and for developing assimilation techniques for the use of satellite data.
- ° Conduct concomitant theoretical studies to improve the models and the use of satellite data in the models.
- ° Develop in-house expertise to advise NASA on hardware and mission development in support of air-sea interaction studies from satellites.

4.5 New Sensors and Measurements

The development of new measurement techniques must be grounded in a firm understanding of existing instruments and their major sources of inaccuracy. As noted in Section 3, present instruments are not adequately known. There exists a need to describe accurately the instruments, the ways data are processed, the sources of error (noting those that arise within the atmosphere or on the surface and thus are likely to produce spurious climatic correlations), and the exact quantity that is being measured. Does a scatterometer measure wind velocity, total stress, or that part of the stress that produces ocean surface waves? Do radiometers measure surface temperature that is representative of the mixed layer, or a skin temperature that is influenced by radiation from clouds and by evaporative cooling? Clear answers to these questions will require carefully designed joint programs involving oceanographers and the remote sensing community.

The development of new instruments must also be grounded in a firm understanding of the usefulness and limitations of present data sets. While few instruments were designed or optimized for the study of climate, existing instruments have produced large sets of data useful for this purpose. These sets must be analyzed to determine what variables need be measured and with what accuracy. [4.3] For example, can variables

observed directly from space, such as spectral radiance, be used as climate indicators in the same way as we presently use quantities observed directly at the surface, such as temperature? [3.5] If so, this would greatly simplify monitoring from space. The existing data must also be used to determine whether or not data from various instruments can be combined to obtain new measures of useful variables. For example, no instrument directly measures the flux of latent or sensible heat, but observations of sea-surface temperature and wind, when combined with observations of water vapor in the lower atmosphere from sounders may provide these variables in regions of high flux.

Because useful indicators or predictors of climate are not well known, and because analyses of existing data are likely to change our opinion of what must be measured, the development of new instruments must again jointly involve climatologists, oceanographers, and the remote sensing community.

It is clear that an evolutionary improvement of instruments will be needed. Some specific recommendations are:

- ° Continued high priority should be given to improving measurements of rain rate even though net rainfall is the variable of direct interest.
- ° The development of atmospheric sounders capable of measuring temperature and water vapor within the atmosphere as close to the sea surface as possible should be supported.
- ° Other desirable measurements include salinity, sea-ice thickness, heat flux by means of infrared radiances at two wavelengths, and height of the boundary layer. Appendix A discusses the present satellite capabilities in these and other areas.
- ° We strongly endorse the development of, and experimentation with, active systems such as lidar (e.g., to measure the height of the boundary layer).

Going beyond conventional instruments, we recommend that NASA consider the development of instruments that include, as an essential part of the system, components placed at the ocean surface. By emitting radiation or by telemetering information, instruments at the surface can substantially improve satellite capabilities. [3.4]

- ° As part of this work, we recommend development of a low-cost method for determining the position and identification of buoys at the surface. Pop-up drifters deployed in relatively large numbers, when combined with observations of sea-surface topography and wind stress, will contribute substantially to our understanding of ocean current systems. [2.3]
- ° Closely allied with the need for surface measurements combined with space systems is a clear requirement for the systematic use of ships of opportunity and for oceanic calibration stations. [3.2, 3.4] The oceanic stations will require accurate instruments

capable of operating unattended in the marine environment and capable of measuring such items as net long- and short-wave radiation and surface relative humidity (or water vapor). Such instruments would greatly enhance the usefulness of space data, but they do not yet exist. We recommend that they be developed as part of a complete climate observing experiment.

4.6 New Missions

A number of new spacecraft missions are currently under consideration (TOPEX, ICEX, NOSS -- See Appendix B). We recommend that air-sea interaction experimenters be closely involved in the planning and implementation of these missions in order to ensure that air-sea interaction program requirements (such as long-term continuity and accessibility of data) are appropriately addressed.

ICEX is part of a broad cryosphere program which may or may not include a dedicated spacecraft. Air-sea interaction objectives and instrumental concepts to meet them are at an earlier stage of development, but ICEX is entirely consistent with our aims and we strongly endorse it.

The possible rewards from analysis of SEASAT, JASIN, MARSEN and other available data sets are sufficiently great that a specific, dedicated air-sea interaction mission should not be defined at the present time. However, such a mission will ultimately be necessary. To what extent TOPEX and NOSS can be modified to achieve our objectives is not yet clear, but it should become clearer in the near future as data analyses become available. We recommend that planning for an air-sea interaction mission be an early task for the Science Steering Group (see Section 5).

4.7 Field Experiments

Space and surface measurements must be related, both to establish relationships and, to some degree, for continuing experimentation. This requires field experiments at all stages of our investigations. This can only be done with field experiments specifically designed to answer key questions about remote sensing instruments or to understand in depth the physical processes relating remotely sensed signals and climatological variables of interest. Examples of such field experiments are given below.

4.7.1 Climatic Monitoring

Specific ground measurements are required in order to extend and improve the "Budyko" maps and parameterizations. There is a specific need to improve the radiation bulk parameterizations using satellite data. This could be done first with JASIN/SEASAT data, followed by a one-year time series provided by aircraft, ships or island stations at 3-4 locations. The data should eventually be related to existing TIROS and planned ERBE and NOSS measurements. (See Appendix B.) In any case, the data must be taken over water to be representative. Based on satellite data, the new bulk formulae will be representative of mean data as opposed to point data and are that much more useful for mapping. [2.2]

4.7.2 Experiments Which Utilize Satellite Data in Support of Process Studies

Two experiments are used here as examples of such integrated space/in situ studies:

I. A Wind Evaluation Experiment

This experiment requires a systematic, careful, highly-tuned evaluation of satellite wind measurements over the range of air-sea interaction conditions relevant to climate. [2.2, 2.3c] These include: high winds and seas, high stability, strong convection, and rain. Measurements must be taken over deep water (unlike MARSEN). The relevant surface variables to which the satellite observables are to be related include: surface wind, direct surface stress, stability, precipitation, surface currents (top 10 cm), and sea state. The measurements of some of the required variables (e.g., surface currents and stress) are experimental and need extensive development.

The philosophy we suggest is one of a series of small, dedicated development experiments aimed at assuring the quality of the surface truth measurements, followed by the definition and testing of an evaluation experiment involving the combined use of surface truth and satellites/ aircraft, followed by a highly-tuned series of actual evaluations in the range of desirable environmental conditions.

II. An Equatorial Dynamics Experiment

The objective of this study is to determine the relationship between circulation and forcing in the basin-wide tropical Pacific region where the atmosphere and the ocean are tightly coupled on climatic time scales. [2.1, 2.3] This will require measurements of surface currents and winds and measurement of the mixed layer heat balance (the heat input and the heat stored) in order to show the effect of advection in the mixed layer on the heat balance on the large scale.

Such a basin-wide experiment should be done in conjunction with the ongoing EPOCS study sponsored by NOAA and the planned PEQUOD being proposed to NSF. The time frame is 1982-85, extending over at least two years to define the annual cycle. Measurement needs include sea level (sea surface topography by satellite), SST, wind stress, heat flux at surface, and temperature and salinity in the mixed layer (in situ measurements from islands, ships, buoys).

5. SCIENCE PROGRAM MANAGEMENT

In this report we have described the first steps in an evolutionary process which should lead to an adequate understanding of air-sea interaction processes for purposes of climate prediction. Effective progress involves important issues of science management.

Collaboration is essential between several agencies (NSF, ONR, NOAA, NASA) and the National Climate Program Office. Inside NASA a close integration is required between the efforts of management, engineers at NASA centers, and scientists inside and outside government. A continuous review of science progress and directions is essential. To provide a forum for such discussion and a focus for the entire program, we recommend the immediate creation of a Science Steering Group (SSG).

SSG membership should consist, principally, of actual or potential investigators in the field of air-sea interaction, chosen by open solicitation. It should be funded adequately and must be supported by staff and engineers from appropriate centers. The SSG should be able to review and modify its own tasks and to initiate activities when necessary. Amongst these tasks are:

- Review the involvement of the oceanographic and atmospheric institutions and communities in the air-sea interaction program and make proposals, where necessary, for steps which will lead to the highest quality of scientific participation;
- Recommend inter-agency activities necessary for effective air-sea interaction studies and steps required for effective science management and funding;
- Review progress in "surface truth" studies and recommend further steps to ensure proper interpretation of space data; [3.3, 4.7]
- Recommend procedures to ensure optimal design of joint space-based and ground-based measurements and unified analysis of the data; [3.4, 4.4]
- Design third and fourth generation data archives and monitor their development; [3.6, 4.4]
- Review instrumentation and orbital requirements for NOSS, TOPEX and other relevant missions and participate in their planning and execution; [4.6]
- Consider requirements for continuity of climatological data from new operational systems; [4.6]
- Initiate the planning process for an air-sea interaction satellite system; [4.6]
- Monitor progress in field experiments; [4.7]
- Advise headquarters on the quality and timeliness of research proposals;

- Recommend, where necessary, the creation of process teams to cut across programs and agencies and to provide a focus on science objectives in specific areas, e.g., wind stress;
- Review programs and facilities in this and other countries to ensure maximum utilization of funded efforts;
- Etcetera.

The SSG should periodically review each aspect of the air-sea interaction program and prepare an annual report to OSTA for circulation and possible external review.

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APPENDIX A: PRESENT REMOTE SENSING CAPABILITIES

In this section we give a brief assessment of the accuracy and resolution of remote sensing measurements relevant to air-sea interaction studies, describe the sources of errors in the retrieved geophysical parameters, and give a near-term projection of expected improvements.

1. Sea Surface Temperature (SST)

SST has been obtained by remote sensing in the microwave and infrared parts of the spectrum. The present standard deviation (RMS) in absolute accuracy is 1-2 K (4 K in some cases). In the infrared, clouds and water vapor introduce significant sources of error. When clouds are not present, the high spatial resolution IR data have revealed the presence of sharp fronts in the ocean which strongly suggests that small scale features differing by less than 1 K could be observed on a relative basis. This high spatial resolution capability of IR methods could also be exploited to reduce the effects of cloud interference. Other sources of errors in the IR techniques are due to the variability of atmospheric water vapor which attenuates the emitted sea surface radiance in the $11\ \mu\text{m}$ window region. Making observations in the $3.7\ \mu\text{m}$ window region will minimize the water vapor contamination, but the effects of reflected solar radiation will most likely restrict the use of this band to nighttime observation only. The field of view of IR techniques is $\sim 1\ \text{km}$.

The microwave technique of measuring SST depends on multispectral measurements. Although the microwave technique can be used in nonprecipitating cloudy areas, sea surface roughness strongly affects the surface microwave emissivity. The field of view of the microwave method at present is $\sim 100\ \text{km}$. Combining the microwave and infrared information on SST (see Section 3.4) may push the RMS error down to 1 K, but probably not below that.

2. Air-Sea Temperature Difference

The air-sea temperature difference may be obtained from measurements of the surface emission in "super spectral windows" located near $2505 \pm 2\ \text{cm}^{-1}$ and $2686 \pm 2\ \text{cm}^{-1}$. In principle the use of these super windows at night, together with atmospheric temperature sounding information, could give the air-sea temperature difference to $\pm 1\text{K}$. The derived temperature difference at the surface is, however, a "weighted" difference because the vertical resolution of current broad-band temperature sounders is 2 - 3 km near the surface. Numerical and experimental verifications of this approach under various atmospheric conditions are still required. Future (~ 5 years) instrumentation such as the high-resolution "Advanced Meteorological Temperature Sounder" (AMTS), currently under design study, could provide a realistic test of this approach.

3. Sensible Heat Flux

The sensible heat flux can be estimated from bulk formula using wind speed and air-sea temperature differences, the latter being the most difficult measurement. UHF or IR multifrequency radiometers can give sea surface temperature and the profile of atmospheric temperature, both with errors of 1 - 2 K, with a difference on the order of 2 K. With these errors the sensible heat flux cannot be estimated to better than a factor of 2, except in those regions of large fluxes produced by cold air masses blowing over warm seas.

Uniform air flow appears to produce rougher sea surfaces when blowing over warm water than over cold water, allowing cold and warm eddies to be seen in satellite photos of sun glint. A radar can measure the roughness, and if the wind speed is known independently the heat flux may be inferred, but again, with little accuracy.

4. Latent Heat Flux

The capability to measure latent heat flux has only been demonstrated with sensors mounted on airborne platforms. Present aircraft capability involves the use of Lyman Alpha and turbulent velocity measurements from which the flux is determined by cross-correlation of signals. The possibility exists for measuring relative humidity near the air-water interface with lidars from which flux measurement can be derived if mean wind speed is known at the surface.

The water vapor profile and the temperature profile that are needed to get relative humidity are at present remotely sensed by IR techniques. Errors present in both these profiles then lead to errors in relative humidity profiles. Errors in relative humidity generally tend to be small near the surface ($\pm 15\%$) and grow with height, since the remote measurements are most sensitive to the lower layers which contain most of the water vapor. Vertical resolution is of the order of 2 to 3 km and some important features in the boundary layer cannot be resolved. Active systems using lidars may be able to achieve better vertical resolution.

5. Radiative Flux

The flux of radiation from the sea is not directly observable from space, but may be inferred from other measurements. Incoming radiation at the surface can be estimated from the percentage cloud cover and is relatively well known. Net outgoing radiation (at long waves) can only escape through a few spectral windows whose transparency is governed mainly by clouds and water vapor. Percentage cloud cover, when coupled with profiles of humidity, may allow the transparency to be estimated accurately. Although these techniques have not been used to monitor the radiative flux through the sea surface, the difficulties do not appear severe, and the calculation should be attempted.

The amount of clouds (defined as the product of the horizontal cover and the cloud emissivity) has been derived from infrared sounders flying on the NIMBUS and TIROS series. The accuracy is $\pm 5\%$ for high clouds above the 500 mb level. This accuracy deteriorates sharply for clouds near the surface (1000 - 850 mb) as the surface emission becomes comparable to that of low-level clouds. Combined visible-IR observations could help solve this problem, and future sounders such as the AMTS may resolve up to three cloud layers as seen from above.

At present the cloud top level is derived with an accuracy of ± 0.5 km and the cloud top temperature is obtained with an accuracy of ± 1 K.

6. Precipitable Water Over Oceans

Both the microwave and infrared remote sensing techniques, using satellite data, can sense the total water vapor content in a column of atmosphere over the oceans to an accuracy of ~ 0.3 g/cm². This corresponds to roughly 10% accuracy over the tropics while at high latitudes the error may be as large as 50%.

The infrared techniques generally require an estimate of the sea surface temperature from satellite observations in water vapor window regions ($11\mu\text{m}$ or $3.7\mu\text{m}$). At least one measurement in the water vapor absorption band (such as $18 - 20\mu\text{m}$) is also needed. The IR technique allows a relatively fine field of view ~ 3 km, but suffers from cloud contamination. To generate a global map of precipitable water over oceans one needs to composite IR measurements for a long time (a few weeks).

The microwave technique using observations in the water vapor resonance line around 22 GHz and a window near 31 GHz has demonstrated that the total column water vapor over the oceans can be successfully mapped in less time (about a week) as the nonprecipitating clouds do not hinder the mapping strongly. Multifrequency techniques based on SMMR (see Appendix B) data show a total precipitable water estimate of similar accuracy. The field of view of microwave measurements is at present large, ~ 30 km.

The errors in both IR and microwave total water estimates stem from significant changes, especially near the surface, in the vertical profile of water vapor and the associated temperature profile. The passive infrared methods described above have a limiting vertical resolution of about 2 to 3 km in the lower troposphere.

Numerical studies have shown that high spectral resolution infrared observations in the water vapor window located at 1930.1 ± 1.5 cm⁻¹ can resolve the amount of precipitable water vapor in the lowest 1-2 km of the atmosphere with an accuracy of 20%. Active systems such as lidars can give better vertical resolution.

7. Rainfall

Rainfall rates have been estimated by observing cloud top height and density using visible and infrared radiation (on the assumption that thick, dense clouds rain more than thin clouds), and by observing radio energy emitted by liquid water (but not ice) at radio wavelengths near 2 cm. This latter method has an accuracy of around $\pm 50\%$, with spatial resolutions on the order of 30 km. The accuracy of the radio technique is limited primarily by inadequate spatial resolution and by the uncertainty in our knowledge of the height of the freezing level and of the distribution of raindrop sizes; the latter can perhaps be estimated from other satellite data (although this has not yet been done). Temperature sounding can be used to estimate the height of the freezing level and observations of scatter from rain (perhaps using the scatterometer) place additional constraints on possible drop-size distributions. Since the large area observed by the radiometer fails to resolve raincells, and the nonlinear relationships between rain rate and radio emission ensures that the areal average of brightness is an imprecise indication of the areal average rain rate, additional data, possibly from the synthetic aperture radar, are needed to accurately estimate rain cell size. Increased spatial resolution provided by larger radiometer antennas will also greatly reduce error.

Because the sources of error are well known, and because they may be reduced using additional data, estimates of rain rate may achieve $\pm 25\%$ uncertainty in five years. Already, the measurements are more accurate than both the existing source of data (ships) and the interannual variability over some large areas.

8. Salinity Measurement

The measurement of salinity has been demonstrated so far only with airborne sensors operating in the 1 GHz band. This sensor provides salinity in the range of 5 - 40 ppt with an accuracy of ± 1 ppt and a resolution of ± 0.3 ppt. Further developments in UHF radiometers may provide, in the near future, salinity measurements in the range 2 - 40 ppt with an accuracy of ± 0.5 ppt and a resolution of $\pm 0.1 - 0.2$ ppt. The deployment of such systems from space platforms using large antennas (on the order of 100 m) would permit spatial resolution on the order of 10 km.

Airborne lidar can also measure the salinity profile, and details on this capability should be available in late 1979.

9. Wind Stress

A. Magnitude

The magnitude of the wind stress can be measured by passive (radiometric) and active (scatterometric) microwave remote sensing techniques. At present, the accuracy assessment based on a comparison of SEASAT data with in situ neutral stability wind speed measurements is: deterministic biases of 1-3 m/s and random standard deviations of 1-2 m/s.

The accuracy assessment for wind stress is more difficult because few direct measurements exist with simultaneous microwave observations. Therefore, the assessment will be accomplished by calculating stress from in situ wind measurements using planetary boundary layer models. This procedure can introduce systematic error of 10% - 20%. Spatial resolutions are presently 20 - 50 km, although future systems may be in the 1 - 10 km range. Higher spatial resolution produces a larger sampling variability because of the microscale turbulence of the wind. Additional research is required to develop geophysical algorithms to include second-order effects such as sea state, surface current, fetch, water viscosity, etc.

B. Vector

The vector wind stress can presently be remotely sensed only by the microwave scatterometric technique. (Optical lidar techniques using scattering from aerosols in the lower atmosphere have been proposed, but this technique requires significant technological, hardware and software development.) Accuracy assessment based on SEASAT data and in situ wind direction measurements yields small biases of 0 - 3 deg, and random standard deviations of $\pm 10 - 20$ deg. Spatial resolution and future research requirements are the same as those for the magnitude measurement.

10. Ocean Current Velocity Measurements

The ocean current velocity is determined by measuring the current speed and direction as a function of position and time. There are three methods for accomplishing these measurements. They are:

i. Doppler Frequency Measurements

The feasibility of using the Doppler frequency shift of a transmitted electromagnetic wave as a means of measuring the current velocity has been demonstrated using measurements from fixed platforms. The ability to perform such measurements from orbital altitudes requires additional conceptual study as well as further instrument design. Specifically, studies should consider the effect of the satellite velocity on the Doppler measurement, and whether the satellite velocity can be determined accurately enough. The effect of the degradation in the amplitude of the Doppler signature with altitude should also be considered. Finally, to extract the current velocity, methods for correcting the measurements for the wave velocity must be developed. The Doppler approach shows considerable promise and should be pursued.

ii. Height Measurements

The ability to infer geostrophic surface velocity using precise height measurements by a satellite altimeter has been demonstrated using both GEOS-3 and SEASAT altimeter data. The present instrument capability (10 cm for a 1 second average) should improve to 7 cm accuracy for the next generation of radar altimeters. Horizontal resolution will vary from 1.6 to 12 km. Range (height) and frequency dependent measurements are affected primarily by the satellite motion which appears as a superimposed signal. The orbit determination accuracies achieved during the SEASAT

mission lead to errors on the order of 50 cm in selected regions and of a meter for the global orbits. Accuracies needed for ice mapping missions or oceanic circulation studies require 2 - 5 cm accuracies for the radial component of the satellite orbit. Such accuracies can be achieved, but further study of the important sources of error are required. These sources include: 1) unknown geoid at satellite heights, 2) outgassing (change of satellite mass), and 3) uncertainty in atmospheric drag.

A different approach involves direct measurements of the slope of the ocean surface with large-antenna multi-beam radar altimeter systems. In this multibeam approach, the radar measurements are processed as a radar interferometer. The development of these radars, now in the conceptual stage, appears quite promising.

iii. Drifting Buoys

The accuracy of the drifting buoy method depends on the accuracy with which the range-rate measurements between a satellite and buoy can be used to determine the position of the surface buoy. The noise level of the determination will be dependent on the strength of the ocean current velocity. Measurement accuracy will depend on understanding over what scales velocity components are being measured. The basic motivation for buoy deployment is that thousands of low cost (~ \$100) buoys can be deployed for the same cost as a high capability, but expensive satellite system. Fewer buoys could still provide surface calibration points for velocity fields derived from Doppler and altimeter data.

11. Sea Level

The primary factors affecting sea level measurements are the accuracies of the radial component of the satellite orbit and of the altimeter measurement. Since the noise in altimeter height is on the order of 5 cm, this measurement will not be the limiting factor. Other factors include atmospheric refraction effects, barotropic pressure effects, tides, currents and other dynamic topography. At present, sea level can be determined to within 20 - 50 cm, and an accuracy of 5 - 10 cm may be possible. It should be noted that for most oceanographic applications, the required measurement is not absolute sea level but rather the slope and its temporal variation which is important. (See item 10 of this Appendix.)

12. Remote Detection of Thermocline Depth

Several methods have been suggested for remote measurement of the oceanic thermocline using space-based techniques. These include:

i. Raman Scattering

Raman scattering laser methods deployed from ships and low-flying aircraft appear capable of extracting temperature profiles of the upper 100 m or so of the ocean. The likelihood of extending this approach to satellite altitude is uncertain, however, because of atmospheric dissipation of the laser beam. Spatial and temporal resolution for this approach

follow orbit constraints similar to altimetry, although some off-nadir sampling may be possible. Future development of the Raman-scattering approach depends first on some clear successes with shipboard experiments.

ii. Internal Wave Dispersion

Internal wave dispersion has been proposed as a method for deriving thermocline characteristics. The dispersion properties of internal waves in the upper layers of the ocean are partially determined by the density gradient across, and the depth of the mixed layer. Internal wave packets are clearly defined as slick patterns under appropriate oceanographic and meteorological conditions. The wavelength of the internal waves may then be measured from images and a phase velocity inferred from the wavelength. Phase velocity is directly related to the vertically integrated density profile.

The limitations of this method are numerous and severe. Future developments will depend on the examination of the large set of SAR (Synthetic Aperture Radar) data collected by SEASAT and on future experiments in open ocean internal wave detection.

iii. Satellite-Tracked Drifters

Satellite-tracked drifters with pressure and temperature instrumentation distributed along an attached tail can directly measure sub-surface temperature and current shear in the mixed layer and below into the main thermocline. A low cost per platform would mean that the expenditure for developing new remote sensing satellite instrumentation could be converted into many thousands of drifters. These could be deployed over the world's oceans by ships of opportunity or, as recently demonstrated, by aircraft. Buoy lifetimes of one year are achievable. Such instruments may well be the only feasible means for measuring the sub-surface temperature structure and currents for many years to come.

13. Sea-Level Pressure

A Microwave Pressure Sounder (MPS) is being developed to measure atmospheric pressure at the Earth's surface from an orbiting satellite. It is designed to operate over open ocean, but measurements should also be possible over arctic sea-ice. Design studies have shown that the MPS is potentially capable of 1.5 mb rms error with a loss of data in perhaps 5% to 10% of the situations (where surface reflectivity, cloud thickness or rain conditions are unfavorable). The surface pressure is deduced essentially from a differential absorption measurement at a pair of frequencies in the lower wing of the oxygen absorption band centered on 60 GHz. Other channels (25 to 75 GHz) are used to compensate for temperature, water vapor, surface and cloud effects. With the currently proposed MPS design, operating from an 800 km orbit, surface pressure measurements would be made about 240 km apart. Future technological development in millimeter wave systems and electronic signal processing could potentially improve rms error to 1 mb and increase coverage and resolution.

14. Remote Identification of Surface Objects

Satellite techniques can readily identify and locate the position of "pop ups" which are carried under water by ocean currents. The technological problem which needs to be solved here is the ability to manufacture such instruments inexpensively at the rate of only a few dollars per unit.

APPENDIX B: SATELLITE EXPERIMENTS FOR AIR-SEA STUDIES

Listed and very briefly described in this appendix are recently operating and planned spacecraft experiments that will provide measurements useful for air-sea interaction research. A summary of the relevant spacecraft instruments and mission objectives is given in Table B-I. Table B-II gives the launch date of the spacecraft and some orbital information. A brief description of each of the instruments listed in Table B-I is given below. The instruments are discussed in alphabetical order, and the satellites on which they have or will be flown, as well as the principal investigator (PI) for a given instrument, are identified. Some general comments about STS/Shuttle are also inserted into the list.

AVHRR (Advanced Very-High-Resolution Radiometer/TIROS-N, NOAA-1, B, C, D, E, F, G; PI: NOAA-NESS Staff)

This instrument measures emitted and reflected radiation in visible (0.55 to 0.9 μm), near IR (0.725 to 1.3 μm), IR (10.5 to 11.5 μm), and IR (3.55 to 3.93 μm) wavelengths. From these observations made in a scanning mode, global day and night-time sea-surface temperatures, ice, snow, and cloud cover information can be derived. Spatial resolution of 1.1 km (HIGH) or 4 km (LOW) is possible.

CZCS (Coastal Zone Color Scanner/NIMBUS-7; PI: Hovis, NOAA-NESS)

This experiment utilizes a 6-channel scanning radiometer to measure reflected solar radiant energy. Temperature of coastal waters and currents are obtained from the 11.5 μm channel. Data from channels at 433, 520, 550, 670, and 750 μm are used to obtain chlorophyll concentration, sediment distribution, gelbstoffe concentrations (salinity indicator), and land vegetation cover information. The observing directions can be adjusted to avoid areas of sun glint.

ERB (Earth Radiation Budget/NIMBUS-6, 7; PI: Jacobowitz, NOAA-NESS)

This radiometer observes emitted solar radiation in 10 different channels, and emitted/reflected terrestrial radiation in 12 other channels (0.2 to $> 50 \mu\text{m}$). Four of the Earth-looking channels measure radiation from the entire disc, and eight scanning channels with narrow fields of view measure the angular dependence of Earth short-wave (4 channels) and long-wave (4 channels) radiation. Scanning channel observations are used to model the angular distribution of radiance reflected and emitted. These models are based on a composite of surface characteristics (land, water, mountains, snow, forest, etc.) as a function of season and of cloudiness at observation time. Models are prepared for each of 2070 (~500 km x 500 km) target areas.

Table B-I

SATELLITE MISSIONS WITH AIR-SEA INTERACTION COMPONENTS

Satellite	Relevant Objective	Relevant Instrumentation
ERBS	Earth Radiation Budget Satellite	ERBE
GEOS-3 ^a	Satellite altimetry experiment	RADAR ALT
GOES	Meteorological soundings/Imagery	VISSR/VAS
ICEX	Support for cryospheric studies	IEAS, PIMR, LAMMR, SCAT, WSIR
NIMBUS 6-7	Develop meteorological sounders/Microwave imaging/Radiation studies	ERB, ESMR, SMMR, HIRS, THIR SCAMS, CZCS
NOAA-1, B-G	Meteorological soundings/Imagery/Albedo	AVHRR, OVS, ERBE
NOSS ^b	Demonstrate operational capabilities for global sea-surface observations	Advanced versions of SCAT, SMMR, RADAR ALT
SEASAT	Ocean geoid/Imaging/Sea-Surface parameters	SAR, SMMR, SR, SASS, RA
STS ^c / Shuttle	Provide platform and transportation system for wide variety of instruments and payloads	
TIROS-N	Operational prototype for NOAA satellite series	
TOPEX	Map sea surface topography	Advanced RADAR ALT

^aGEOS = Geodetic Satellite^bNOSS = National Oceanic Satellite System^cSTS = Space Transportation System

Table B-II
ORBITAL INFORMATION

Satellite	Launch Date	Inclination	Altitude	Period	
ERBS	1984	46°	600 km	97 min	
GEOS-3	4/75	115°	839-853	102 min	
GOES - 1	10/75	1.0°	34165-36458	23.5 hr	ES ^a (57E)
- 2	6/77	0.8°	35266-36304	23.9 hr	ES (75W)
- 3	6/78	1.7°	35469-36679	24.2 hr	ES (135W)
- D	1980	1.0°	35786	24.0 hr	ES (75W)
- E	1981	1.0°	35786	24.0 hr	ES (90W)
- F	1982	1.0°	35786	24.0 hr	ES
ICEX	1985	87°	700	-	
NIMBUS-6	6/75	100°	1093-1101	107 min	SS ^b
-7	10/78	99°	938-953	104 min	SS (12:00)
NOAA -1	6/79	99°	807-823	101 min	SS (19:30)
-B	1981	99°	833	102 min	SS (15:30)
-C	1982	99°	833	102 min	SS (19:30)
-D	1983	99°	833	102 min	SS (15:30)
-E	1984	99°	833	102 min	SS (19:30)
-F	1985	99°	833	102 min	SS (15:30)
-G	1986	99°	833	102 min	SS (19:30)
NOSS	1985	85-100	≥600	-	
SEASAT	6/78	108	769-799	101 min	
STS/Shuttle	1980+	-	low orbits	-	
TIROS-N	10/78	99	846-862	102 min	SS (15:00)

^aES = Earth Synchronous Orbit (longitude of equatorial crossing)

^bSS = Sun Synchronous Orbit (local time of equatorial crossing)

ERBE (Earth Radiation Budget Experiment/ERBS, NOAA-F, G; PI: Barkstrom, NASA-LaRC)

This 8-channel radiometer measures the energy exchange between the Earth-atmosphere system and space. The experiment is presently planned to be flown on two sun-synchronous NOAA satellites (to make high latitude observations) concurrently with the ERBS (which will make mid- and low-latitude observations). The instrument consists of a wide/medium field of view (FOV) package of 5 channels, and a 3 channel scanner package. On the 5 channel package, 2 channels observe the 0.2 to 5 μm Earth/atmosphere radiance, one at wide angle (135 deg-entire disc) and the other at medium angle resolution (88 deg-Texas size footprint). The other two channels are similar except that the total radiance from 0.2 to $> 50 \mu\text{m}$ is observed. The 5th channel (0.2 to $> 50 \mu\text{m}$) provides a reference observation of the sun and periodically measures the solar constant. The scanner package observes radiances in the short wave (0.2 to 5 μm), in long wave (5 to $> 50 \mu\text{m}$) and total radiance (0.2 to $> 50 \mu\text{m}$). Channels 1-4 are designed primarily for nadir operation, channel 5 (with a 5 deg FOV) for solar viewing, and the 3 scanning channels (with a 3 deg FOV) for crosstrack scanning from horizon to horizon.

ESMR (Electrically Scanning Microwave Radiometer/NIMBUS-6; PI: Wilheit, NASA-GSFC)

This Dicke-type radiometer and its phased-array antenna observes Earth microwave emissions at 37 GHz (0.8 cm). The antenna scans in 100 discrete steps to make observations up to ± 35 deg from nadir along the sub-satellite track. Brightness temperatures can be interpreted in terms of cloud liquid water content, distribution and variation of sea ice, rainfall rates, and gross characteristics of land surfaces (snow cover, soil moisture, vegetation, etc.).

HIRS (High-Resolution IR Sounder/NIMBUS-6; PI: Smith, NOAA-NESS)

This 17 channel scanning ($\pm 30^\circ$ from nadir) radiometer observes Earth reflected and emitted radiances between 0.69 and 15 μm . Derived parameters include temperature sounding for colder regions and cloud amounts/heights (7 channels from 13.4 to 15.0 μm), surface temperature and cloud mapping (11 μm), water vapor sounding and thin cirrus mapping (6.7 and 8.2 μm), temperature sounding for warmer regions (5 channels from 4.24 to 4.57 μm), surface temperatures (3.71 μm), and cloud mapping (0.69 μm).

IEAS (Ice Elevation Altimeter System/ICEX)

The IEAS would be made up of two major subsystems; a Radar Altimeter system operating at 13.5 GHz, and a Laser Altimeter subsystem (ND:YAG) which operates in the near IR at 1.061 μm with a 200 picosecond pulse and pulse repetition of 10 to 20 per second. For both subsystems, travel time, and return signal characteristics are observed. Derived observables include sea-ice concentration, albedo, ice sheet boundaries, slopes, roughness, and elevations; significant wave heights and wind speeds over ice-free areas;

location and velocity of polar ocean currents. This system would utilize technology developed with the GEOS-3 and SEASAT altimeter programs.

LAMMR (Large Antenna Multi-Frequency Multichannel Radar/ICEX)

This dual linear polarized, scanning microwave radiometer would observe microwave brightness temperatures in 7 channels between 1.4 and 91 GHz (21.4 and 0.32 cm wavelengths). Measurements to be derived from these observations include sea ice (concentration, melting, and temperature), ice sheet (elevation, accumulation rate, surface temperature, melting rate) and snow cover (snow depth, water equivalent, percent cover, and free water content) parameters. This instrument would be developed from the earlier SMMR flown on NIMBUS-7 and SEASAT.

OVS (Operational Vertical Sounder/NOAA-1, B, C, D, E, F, G;; PI: NOAA-NESS Staff)

This sounder is a composite of 3 instruments observing reflected and emitted radiances with a total of 27 channels ranging from 3.7 μm to 57.9 μm . The instruments are a 20-channel, high-resolution IR spectrometer (HIRS/2), a 3-channel stratospheric sounding unit, and a 4-channel microwave sounding unit. From the observed radiances, temperature and humidity profiles from the Earth's surface up into the stratosphere (~1 mb) can be obtained.

PIMR (Polar Ice Mapping Radiometer/ICEX)

This five-channel scanning radiometer would observe emitted and reflected radiation in the near and thermal IR portion of the spectrum (0.754, 0.863, 1.14, 1.64, and 11 μm). The observations can be interpreted as temperature maps with a spatial resolution of 1 km, and thermal resolution of 0.1K. Differentiation can be made between clouds and ice (snow), and between melting, re-frozen and fresh ice (snow). This instrument would be a modified version of the AVHRR-2 flown on Tiros-N type spacecraft.

RA (Compressed Pulse Radar Altimeter/SEASAT; PI: Tapley, University of Texas at Austin)

RADAR ALT (Radar Altimeter/GEOS-3; PI: Purdy, NASA-WFC)

Radar Altimeters measure round trip travel time, returned signal strength and waveform. The derived parameters include spacecraft-ocean surface distance, wave height, ocean-surface slope, ocean-surface currents, and sea state.

SAR (Coherent Synthetic Aperture Imaging Radar/SEASAT; PI: Teleki, USGS)

Radar signals are interpreted as images of the ocean surface. Waves with wavelengths between 50 and 1000 meters can be identified. Wave direc-

tion and height can also be determined. Ice, oil spills, current patterns and other similar features can be identified. Images are available in clear and cloudy areas, including areas with nominal rain.

SASS (SEASAT Scatterometer System/SEASAT; PI: Pierson, CUNY)

Radar signal (14.6 GHz) strength returns were observed across a 1500-km-wide, sub-satellite swath. The 250 km outer edges of the swath provide only wind speeds, and the central 140 km of the swath are under special study. Observations of the remaining portion of the swath are interpreted as wind direction and speed.

SCAMS (Scanning Microwave Spectrometer/SEASAT; PI: Staelin, MIT)

This 5-channel Dicke-type superheterodyne radiometer observes thermal radiance between 4.6 and 13.5 mm (55.4 and 22.2 GHz). Data from the three low wavelength oxygen channels at 4.6, 4.9, and 5.7 mm (22.2, 22.24 and 31.65 GHz) are used to obtain water vapor and cloud water content over calm oceans. Observations are not blocked out by clouds. Scanning $\pm 45^\circ$ from nadir provides broad coverage with resolution of 145 km near nadir to 330 km near the scanning limit.

SCAT (Scatterometer/ICEX)

This instrument would observe radar signal strength returns (14.6 GHz) across a 1500 km wide sub-satellite swath. Derived data (incorporating input from the LAMMR) includes ice type, ice concentration, ice sheet roughness, ice ridging characteristics, and wind vectors over ocean areas. This instrument would be an upgraded version of the SASS.

SMMR (Scanning Multichannel Microwave Radiometer/NIMBUS-7; PI: Gloerson, NASA-GSFC/SEASAT; PI: Ross, NOAA-ERL)

This 10-channel (five-frequency, dual-polarized) scanning radiometer observes microwave brightness temperatures at wavelengths of 0.8, 1.4, 1.7, 2.8, and 4.6 cm (37, 21, 18, 10.69 and 6.63 GHz). From these observations, low-level winds, water vapor, liquid water content, mean cloud droplet size and ocean ice versus water can be determined. These ocean-momentum and energy-transfer parameters are obtainable on a nearly all-weather basis.

SR (Scanning Visible/IR Radiometer/SEASAT; PI: McLain, NOAA-NESS)

This is a 2 channel radiometer observing reflected radiation in visible wavelengths (0.52 to 0.73 μm) during the day, and emitted IR radiation (10.5 to 12.5 μm) during day and night. Derived observables include surface temperatures (land, sea, and cloud-top) and imagery of visible and thermal features such as clouds, storms, and ocean currents.

STS/Shuttle (Space Transportation System)

STS/Shuttle will be the standard vehicle by which future satellites are launched. Some spacecraft mentioned in this appendix have already been assigned a launch vehicle, such as GOES-D to STS-4. In addition to transportation of spacecraft, the shuttle vehicle itself will be used as a base from which to conduct experiments for as long as 30 days. Efforts are presently underway to define useful experimentation relative to air-sea studies, which may take advantage of the shuttle flight characteristics. Some possibilities for flight in 1984 through 1986 include Lidar (surface and shallow bottom topography observations), MW radiometry (sea surface temperatures, salinity), scatterometer (low-level winds), altimetry (current velocities, ice and sea topography, sea state), and IR radiometry (sea surface temperatures, total water vapor content).

THIR (Temperature, Humidity Infrared Radiometer/NIMBUS-6, 7; PI: McCulloch, NASA-GSFC)

This instrument detects thermal radiation emitted in the 10.5 to 12.5 μm IR region and in the 6.5 to 7.0 μm visible region. The IR channel data can be interpreted in terms of cloud-top temperatures, high-resolution cloud-cover imagery, and land/water thermal gradients (in cloud-free regions) during both day and night. Radiance observations from the visible channel can be interpreted in terms of water vapor at upper tropospheric, and stratospheric heights.

VAS (VISSR Atmospheric Sounder/GOES-D, E, F; PI: Shenk, NASA-GSFC, and NOAA-NESS Staff)

VISSR (Visible IR Spin Scan Radiometer/GOES-1, 2, 3; PI: NOAA-NESS Staff)

The VISSR and VAS instruments are closely related in that the VAS is an improved VISSR with a capability for atmospheric sounding. VISSR is a 2 channel scanning radiometer capable of providing both day and night Earth-ocean/cloud radiance measurements. The visible channel (~ 0.55 to $0.75 \mu\text{m}$) scans with 8 detectors to provide 1 km resolution at nadir. The IR channels (~ 10.5 to $12.5 \mu\text{m}$) provide 9 km resolution at nadir. A full scan cycle requires 20.2 minutes. The VAS capability provides IR radiance observations at 12 wavelengths between 3.9 and $14.7 \mu\text{m}$ and adds two imaging modes and a sounding mode to the VISSR. The VAS also makes possible IR resolution of 6.9 or 13.8 km in the imaging modes and 13.8 km in the sounding mode. Meteorological parameters derived from the VISSR include cloud cover, Earth/cloud temperatures, cloud-type, cloud-motion derived winds, and stereo-derived cloud top heights. Parameters added from the VAS capability include water vapor and temperature fields, improved surface temperatures, improved cloud type specification, and temperature/moisture profiles for both clear and partly cloudy areas. For cloudy areas, cloud type identification is improved. The VAS improvement for VISSR is an experimental effort by NASA-GSFC and if successful, the new capabilities of VAS will be transferred to NOAA for possible operational applications.

WSIR (Wide Swath Imaging Radar/ICEX)

Radar signal returns (9600 MHz) will be interpreted as images of ice forms, snow, leads and ocean surfaces. Many different parameters can be discerned from the imagery, including percent snow cover; ice sheet velocity; iceberg location, motion and size; sea-ice type and motion. Full coverage poleward of 60 deg is planned every two days.

APPENDIX C: LIST OF WORKSHOP PARTICIPANTS

The first part of the workshop was devoted to presentations on the current status of various air-sea interaction observational programs and to future plans of the major federal agencies in the area of air-sea interaction climate studies. A list of these presentations is given below. The position papers on which the workshop report was based were written in small working groups. A list of the working groups and their chairmen is also given below. This is followed by a general listing of the workshop attendees.

Workshop Presentations

NORPAX (North Pacific Experiment)	T. Barnett
MARSEN (Marine Remote Sensing Experiment)	O. Shemdin
GATE (GARP Atlantic Tropical Experiment)	J. Businger
JASIN (Joint Air-Sea Interaction Experiment)	J. Businger
SEASAT	
1. SAR (Synthetic Aperture Radar)	J. Dunne
2. ALT (Altimeter)	B. Tapley
3. SASS (Scatterometer)	L. Jones
4. SMMR (Scanning Multichannel Microwave Radiometer)	E. Njoku
STREX (Storm Response Experiment)	P. Niiler
MILE (Mixed Layer Experiment)	P. Niiler
EPOCS (Eastern Pacific Ocean Climate Study)	D. Halpern
Global Wind Measurements	E. Hinkley
MONEX (Monsoon Experiment)	C. Friehe
AMTEX (Air Mass Transformation Experiment)	C. Friehe
Future NASA Plans	I. Rasool
Future NOAA Plans	J. Fletcher
Future NSF Plans	P. Hacker
Future NCPO (National Climate Program Office) Plans	E. Epstein
Future ONR (Office of Naval Research) Plans	N. Untersteiner

Working Groups (Chairmen)

1. Oceanic transports and storage (P. Niiler)
2. Physical processes in the ocean surface layer (E. Kraus)
3. The atmospheric boundary layer (J. Businger)
4. Synoptic and climatic responses of the atmosphere to surface fluxes (F. Bretherton)
5. Sea ice (N. Untersteiner)
6. Remote sensing (M. Chahine)
7. Program elements and priorities (R. Goody, Steering Committee)

Workshop Participants

Prof. D. James Baker
University of Washington

Dr. T. B. Barnett* (Executive Officer)
Scripps Institution of Oceanography

Dr. K. Bergman
National Science Foundation

Dr. Robert Bernstein
Scripps Institution of Oceanography

Dr. George H. Borne
Jet Propulsion Laboratory

Dr. Francis Bretherton*
National Center for Atmospheric
Research

Dr. Melbourne G. Briscoe
Woods Hole Oceanographic Institution

Prof. Joost A. Businger*
University of Washington

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